RESEARCH ARTICLE

Decompression Sickness During Simulated Extravehicular Activity: Ambulation vs. Non-Ambulation

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BACKGROUND. Extravehicular activity (EVA) is required from the International Space Station on a regular basis. Because of the weightless environment during EVA, physical activity is performed using mostly upper-body movements since the lower body is anchored for stability. The adynamic model (restricted lower-body activity; non-ambulation) was designed to simulate this environment during earth-bound studies of decompression sickness (DCS) risk. DCS symptoms during ambulatory (walking) and non-ambulatory high altitude exposure activity were compared. The objective was to determine if symptom incidence during ambulatory and non-ambulatory exposures are comparable and provide analogous estimates of risk under otherwise identical conditions. *METHODS.* A retrospective analysis was accomplished on DCS symptoms from 2010 ambulatory and 330 non-ambulatory exposures. *RESULTS.* There was no significant difference between the overall incidence of DCS or joint-pain DCS in the ambulatory (49% and 40%) vs. the non-ambulatory exposures (53% and 36%; $P>0.1$). DCS involving joint pain only in the lower body was higher during ambulatory exposures (28%) than non-ambulatory exposures (18%; $P<0.01$). Non-ambulatory exposures terminated more frequently with non-joint-pain DCS (17%) or upper-body-only joint pain (18%) as compared to ambulatory exposures; 9% and 11% ($P<0.01$) respectively. *DISCUSSION.* These findings show that lower-body, weight-bearing activity shifts the incidence of joint-pain DCS from the upper body to the lower body without altering the total incidence of DCS or joint-pain DCS. *CONCLUSIONS.* Use of data from previous and future subject exposures involving ambulatory activity while decompressed appears to be a valid analogue of non-ambulatory activity in determining DCS risk during simulated EVA studies.
Keywords: DCS, exercise, adynamia, denitrogenation, preoxygenation, prebreathe

Altitude decompression sickness (DCS) is caused by the actions of evolved gas bubbles on nerves and other tissues. The bubbles evolve when tissues and blood, saturated with nitrogen at ground-level pressure, become supersaturated with nitrogen during decompression to altitude. Exercise during altitude exposure has historically been identified as a risk factor for development of altitude DCS symptoms (7,8,9). Ferris et al. (6) and Henry (1945) independently identified and reported the correlation between the region of stress and development of DCS in that region. Motley et al. (10) found DCS more frequently in the shoulders than in the knees. Their profiles at 9144 m to 11,583 m (38,000 ft; 2.99 psia) involved over 60,000 exposures and did not involve any prebreathe for the altitude indoctrination trainees. No walking or exercise was described as part of their exposures. Stewart et al. (17) reviewed data from 16,000 seated (no walking) exposures to 10,668 m (35,000 ft; 3.46 psia) and reported that the incidence of upper-body joint pains (about 60%) exceeded lower-body joint pains (about 40%). More recently, Ryles and Pilmanis (16) studied 1132 hypobaric exposures that involved some walking during exposure. They reported 447 cases of DCS and stated that musculoskeletal complaints were the most frequently reported symptoms (83%, 372/447), of which 70% (262/372) involved knee pain. Henry (8) and Pilmanis et al. (12) investigated the effects of dynamic (frequently called isotonic) versus isometric exercise mode on DCS rates. They reported that onset time, incidence, and severity of DCS pain were not associated with mode of exercise during their exposures which involved some walking while decompressed. During the ambulatory exposures reported by Pilmanis et al. (12), symptoms in the lower body were over 3 times as prevalent as in the upper body.

Interest in mode of exercise as related to DCS incidence increased during studies related to extravehicular activity (EVA) in space. The effects of microgravity on DCS were of particular interest. A ground-based model was developed to simulate the effects of weightlessness during simulated EVA involving altitude chamber exposures (5). This non-ambulatory model was defined as the "adynamic" model (4,13-15). The adynamic model was hypothesized to be more realistic of actual EVA than ambulatory movement under 1-g during altitude chamber exposures, as commonly used during altitude DCS research. This hypothesis is based on the premise that most space "walks" involve primarily the upper extremities, while the lower extremities are anchored for stabilization. During exposures to 9144 m (30,000 ft; 4.36 psia), Vann and Gerth (18) employed simulated weightlessness involving restricted lower-body movement, eliminating any walking during exposure (non-ambulatory). Upper extremities were exercised during these exposures and they (18) reported a large reduction in frequency of lower-body symptoms under non-ambulatory (6% DCS; N=18) vs. ambulatory (53% DCS; N=19) exposure conditions. They did not show a difference in the upper body symptoms when comparing non-ambulatory (11% DCS) with ambulatory (11% DCS) exposure conditions.

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There is a considerable body of information available in the literature in which ambulatory activity was accomplished during altitude exposures. Those data could be of use if ambulatory conditions could be shown to be as effective as a non-ambulatory simulation of EVA. It is more difficult to accomplish altitude exposures on subjects who are not allowed to walk during exposure. Special exercise and monitoring equipment must be used, limiting the number of subjects that can participate in a chamber exposure in most facilities. Alleviating the need for compliance with the strict requirements of non-ambulatory activity during earth-bound exposures (4,18) would allow more rapid and economical completion of protocols designed to support EVA activities. It would also allow use of a large body of research data from altitude DCS research studies that allowed walking during exposure. The primary objectives of this research were to determine 1) if there are any differences in the incidence of joint-pain DCS cases or location that occur during non-ambulatory vs. ambulatory exposure activity, 2) if there is any difference between the incidence of non-joint-pain DCS cases during these two modes of exposure activity, and 3) if there are any differences in the overall symptom incidence during non-ambulatory and ambulatory exposures.

METHODS

The voluntary, fully-informed, written consent of the 413 subjects used in this research was obtained, and the protocols were approved by an Institutional Review Board. All subjects passed an appropriate physical examination and were representative of the USAF rated aircrew population in terms of age, height, and weight. While some subjects participated in only one of the 90 protocol profiles represented, most participated in multiple profiles averaging 5.3 exposures per subject. Information from the 344 subjects' cases of DCS were retrieved from Air Force Research Laboratory's Altitude Decompression Sickness Research Database which contains detailed information on over 2900 hypobaric exposures at the Air Force Research Laboratory High Altitude Protection Research facility located on Brooks City-Base, Texas. Selection of the protocol profiles was based on the nature of activity while decompressed. The 2010 exposures involving walking were included as "ambulatory" mode exposures, and the 330 exposures requiring the subjects to sit or remain supine or recumbent during exposure were included as "non-ambulatory" mode exposures. Exposure parameters varied from zero to 4 h of prebreathe, various exercise-enhanced prebreathe procedures, 5486 m (18,000 ft; 7.34 psia) to 12,192 m (40,000 ft; 2.72 psia) exposure altitudes, 90 min to 8 h of exposure, and rest to heavy exercise during exposure. Most of these parameters are discussed in depth within previous publications from this laboratory (12,19-21). Test termination criteria of the exposures were: 1) completion of the scheduled exposure; 2) development of any signs or symptoms of DCS; or 3) detection of left ventricular gas emboli using echocardiography (11).

Data Analysis. The data from non-ambulatory and ambulatory modes of exposure activity were analyzed to determine the incidence of overall DCS and of joint-pain symptoms. The data from 924 subject-exposures involving joint pain were further divided into those who reported pain only in the upper-body joints (back, elbow, finger, hand, neck, shoulder, and/or wrist) or only in the lower-body joints (ankle, foot, hip, knee, and/or toe). Subject exposures resulting in both upper- and lower-body joint pains were relatively few (N=35; 1.5% of all subject exposures, 3% of all exposures with any DCS) and were not included in further data analyses. Incidences of DCS in the subsets were subjected to Chi Square analyses to determine if there were any differences based on mode of exposure. McNemar's test was used to determine if there was a difference between incidences of upper-body and lower-body joint pain within modes of exposure. When testing at the 0.05 alpha level, and for the sample sizes stated above, the statistical power of the Chi Square test was calculated to be greater than 0.90 for detecting a difference as little as 7% between DCS rates of the ambulatory and non-ambulatory groups.

TABLE I. DCS CASES BY MODE OF ACTIVITY DURING EXPOSURE

Exposure Mode →	All	% of All	Ambulatory	%	Non-Ambulatory	%
Exposure N	2340		2010		330	
·Overall DCS	1166	49.8	992	49.4	174	52.7
··Overall Joint Pain (JP) DCS	924	39.5	805	40.0	119	36.1
···Lower-Body JP DCS only	619	26.5	560	27.9*†	59	17.9
···Upper-Body JP DCS only	270	11.5	212	10.5	58	17.6*
··Other DCS only	242	10.3	187	9.3	55	16.7*

* Higher incidence than during the other mode of exposure ($P < 0.0001$; Chi Square)
† Higher incidence during ambulatory lower-body exposures than ambulatory upper-body exposures ($P < 0.0001$; McNemar's)

RESULTS

All test results are shown in **Table I**. In a preliminary analysis (2), we determined that there was no difference between the incidences of overall DCS symptoms during the two modes of exposure ($P > 0.25$). We found no difference ($P > 0.16$) between the incidences of joint-pain DCS with ambulatory vs non-ambulatory modes of exposure activity.

Non-neurologic DCS skin symptom cases (cold sweat, edema, erythema, hot and/or cold sensation, numbness, pins & needles, tingling, prickling, pruritus, skin mottling) were more prevalent during the non-ambulatory (17%) than during ambulatory (8%; $P < 0.0001$) exposures. Neurologic and respiratory symptoms were not singled out due to their low prevalence, but combined with non-neurologic DCS skin symptoms in the "Other DCS only" category.

DISCUSSION

Conkin and Powell (4) reported a higher frequency of lower-body joint pain whether or not subjects were restricted to non-ambulatory activity. Balldin et al. (1) found that joint-pain DCS cases during non-ambulatory exposures were evenly divided between the upper and lower body. Our data, which includes the Balldin et al. (1) data, indicate a preponderance of lower-body joint-pain DCS only during ambulatory exposures and equivalence during non-ambulatory exposures indicating a large distribution difference between the two modes ($P < 0.0001$). In the Conkin and Powell (4) study, 26 of the 35 ambulatory exposures (74%) with apparent joint-pain DCS involved the lower body. The proportion of DCS due to lower-body-only joint pain in our ambulatory exposures (Table I; 560/772) is a very similar 73%. However, Conkin and Powell (4) came to the conclusion that non-ambulatory activity produces less DCS than ambulatory activity while exposed to altitude because only 60% of the 5 cases of DCS during their study developed DCS in the lower body. Their lack of data on many of the conditions used in their dataset going back to 1942, including level of aerobic activity (VO_2), and clear definition of exposure endpoints during the exposures makes comparisons open to reevaluation in light of the influence of workload on DCS incidence (8,12). Conkin and Powell (4) did not report observation of any skin symptoms. The difference in occurrence of these symptoms between their report and the Balldin et al. (1) report indicates a possible difference in endpoint criteria that could have affected some of the difference. The Balldin et al. (1) study used the same criteria during comparison of non-ambulatory activity to ambulatory activity during exposures which involved the same upper-body exercises at very comparable workloads. Balldin et al. (1) reported no significant difference in DCS incidence between the ambulatory (42% DCS) and non-ambulatory (44% DCS; $P > 0.9$) exposures nor between levels of joint pain DCS (31% vs. 28%; $P > 0.82$).

Our results conflict with the Conkin and Powell (4) report, which states that "Adynamia appears to reduce the total incidence but does not change the distribution of symptoms, at least in this small sample of data." They reviewed 58 non-ambulatory and 176 ambulatory exposures. With only 3 cases of lower-body and 2 cases of upper-body joint-pain DCS during the non-ambulatory exposures, the results were not amenable to statistical comparison of DCS joint-pain location with good power ($P > 0.4$; Power < 0.25). The 9% and 19% joint-pain DCS cases during non-ambulatory and ambulatory modes reported by Conkin and Powell (4) were not significantly different ($P = 0.058$; Power = 37%), although the trend indicated more joint-pain incidence during ambulatory exposures.

Our finding of no difference in the prevalence of joint pain during ambulatory or non-ambulatory exposures (Table I) implies that overall joint-pain incidence is not affected by mode of activity during exposure. The large difference in distribution of joint-pain symptoms with no difference in overall joint-pain incidence is based on a relatively large dataset we used to evaluate the two modes of exposure activity. The difference in distribution of joint-pain DCS symptoms may relate to the methods of equalizing the energy expenditure of subjects performing non-ambulatory or ambulatory activity. To compensate for the lack of energy required to walk during ambulatory exposures, the workload on the upper body under these experimental conditions was likely increased despite efforts to keep the activities as analogous as feasible. An increased upper-body energy expenditure could reflect greater tension on upper-body joints and tendons, which could either lead to more upper-body DCS joint pain or exacerbate undetected symptoms. It may also lead to other symptom development.

The higher level of non-joint-pain DCS symptoms during non-ambulatory exposures was, in part, responsible for equivalence of overall DCS incidence based on exposure activity mode. The more frequent non-joint-pain DCS symptoms under non-ambulatory exposure conditions (Table I; $P < 0.0001$) consisted mostly of skin manifestations and some more serious symptoms. Any concern about joint-pain symptom distribution may be overshadowed by these additional non-joint-pain symptoms during operational activities such as EVA. During EVA, any DCS symptom is cause for concern, and prevention of any symptom is the objective. Continuing an altitude exposure after development of continuous, mild skin symptoms resulted in serious central nervous system symptom development during one of the exposures in this dataset (AFRL Altitude DCS Research Database). Mild skin symptoms such as pins and needles, cutis marmorata (3), hot and/or cold sensation, and other peripheral skin symptoms are valid test termination criteria and are as much reason for concern during EVA as are mild joint-pain symptoms.

There were 128 of the 330 non-ambulatory exposures which met the strict criteria for non-ambulatory conditions defined in the report by Conkin and Powell (4) to include a recumbent position during a 4-h preflight and 3-h exposure. No difference was observed between incidence of upper-body and lower-body joint pains during those 128 exposures ($P > 0.4$; N.S.). Results from this subset of data are in agreement with results from the remaining non-ambulatory exposures reviewed here and demonstrate a difference in where joint-pain symptoms occur based on mode of exposure activity. The findings in this report agree, in part, with Conkin and Powell (4) that the "lower body is the dominant location of pain-only symptoms" because 70% of our pain-only symptoms were in the lower body during ambulatory subject-exposures.

CONCLUSION

The distribution of DCS symptoms during ambulatory and non-ambulatory exposures is relevant to a better understanding of response to various types of movement or exercise. The current analyses show joint-pain DCS was more prevalent in the lower body than in the upper body during ambulatory exposures and the opposite during non-ambulatory exposures. The overall DCS incidence and incidence of DCS joint pain were not significantly different in this comparison of 2010 ambulatory vs. 330 non-ambulatory research chamber exposures. Non-ambulatory activity resulted in a higher prevalence of exposure terminations due to "other DCS only" (non-joint pain) symptoms. These findings are not in agreement with some previous reports that credited non-ambulatory conditions with lower levels of DCS due to reduced incidence of lower-body joint pain.

These findings indicate that ground-based, altitude chamber research aimed at simulating weightless conditions using ambulatory or non-ambulatory activity during exposure produce equivalent levels of DCS joint pain. These findings suggest that future altitude DCS research relevant to EVA can be accomplished using ambulatory or non-ambulatory exposure conditions.

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14. ABSTRACT
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